

The Gravitino and the Swampland

DIETER LÜST (LMU, MPP)

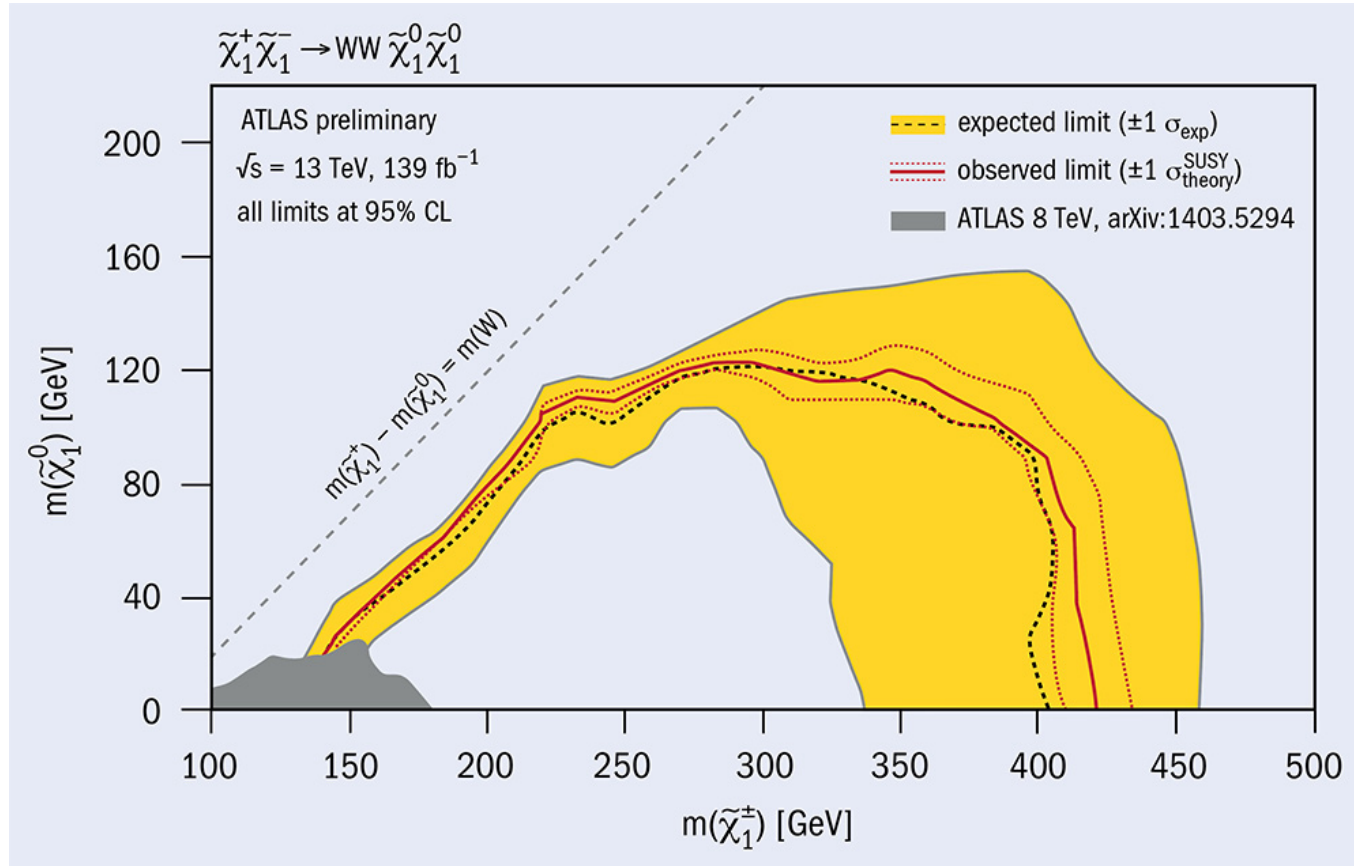


Joint work with Niccolo Cribiori and Marco Scalisi (2021)
and with E. Palti and C.Vafa (2019)

I) Introduction

Apparently low energy supersymmetry is not favoured by experiments:

$$M(\text{Susy partner}) > \mathcal{O}(TeV)$$



Is there any fundamental reason against low energy supersymmetry ??

$\mathcal{N} = 1$ local supersymmetry:

Spin - 2 graviton \longleftrightarrow Spin - 3/2 gravitino
Susy

The gravitino is a very fundamental particle.

The scale of susy breaking is set by the gravitino:

$$M_{SUSY}^2 \simeq m_{3/2} M_P$$

Exp: $m_{3/2} \geq \mathcal{O}(10^{-3} \text{eV})$

Is there any fundamental reason against a light gravitino ??

Here we like to ask the question:

Can we get information about the scale of Susy breaking, i.e. about the mass of the gravitino from basic properties of quantum gravity ?

Similar question can be asked for

- the mass of the graviton or higher spin particles

[D. Kläwer, D.L. , E. Palti (2018)]

- the cosmological constant

[G. Dvali, C. Gomez (2014);
G. Obied, H. Ooguri, L. Spodyneiko, C.Vafa (2018)]

- the number of space-time dimensions

[Q. Bonnefoy, L. Ciambelli, D.L. , S. Lüst (2020)]

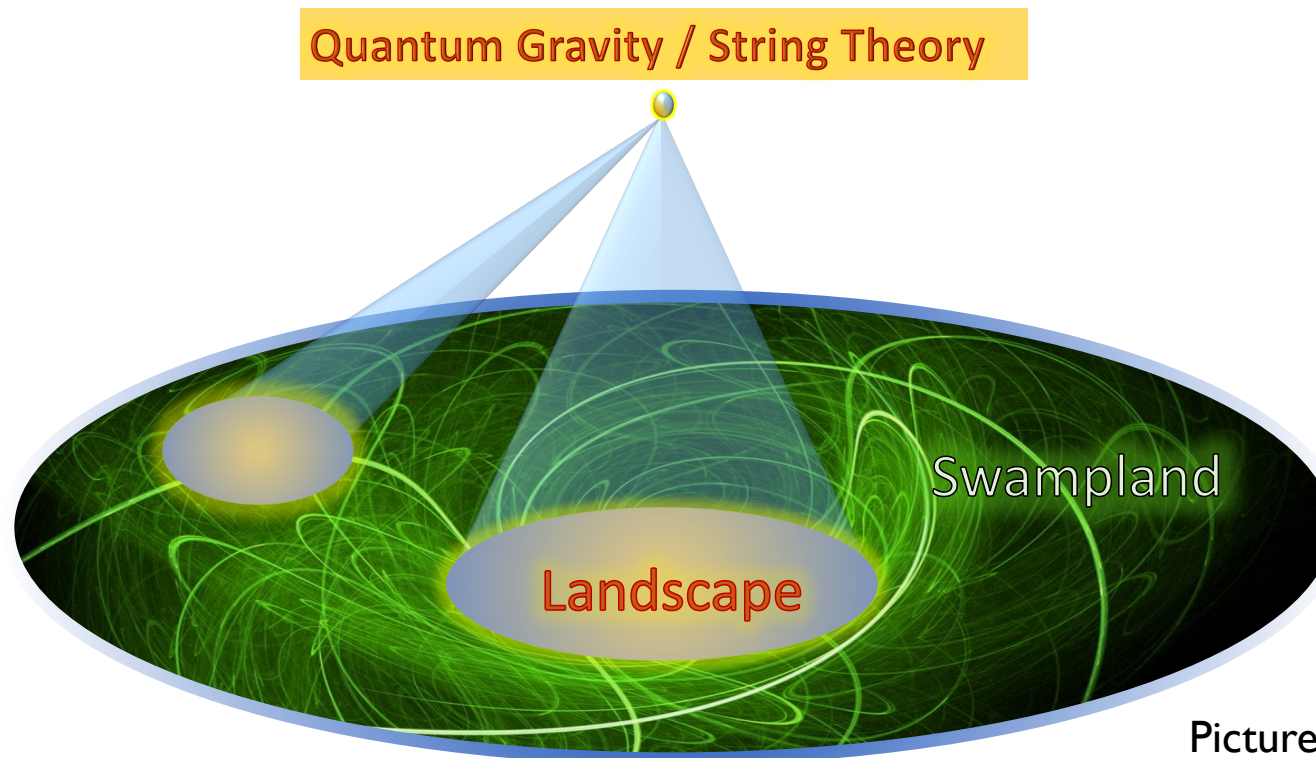
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Swampland program:

[H. Ooguri, C.Vafa (2006)]

[Reviews by E. Palti (2019)
M. van Beest, J. Calderon-Infante, D.
Mirfendereski, I.Valenzuela (2021)]

Which IR consistent quantum field theories cannot be embedded into a UV complete quantum gravity theory?



Picture thanks to Eran Palti

Swampland conjectures:

General conjectures about the boarder line between the landscape and the swampland.

- rigorous and also less rigorous
- less useful and useful in phenomenology
- often motivated from general black hole properties
- often tested in string theory

Here: the gravitino mass conjecture:

- well motivated and also tested in string theory
- quite useful in phenomenology

History of the landscape/swampland:

1985: First string revolution: unique string theory



History of the landscape/swampland:

1986 - : Emergence of the landscape

4D strings: 10^{1500}

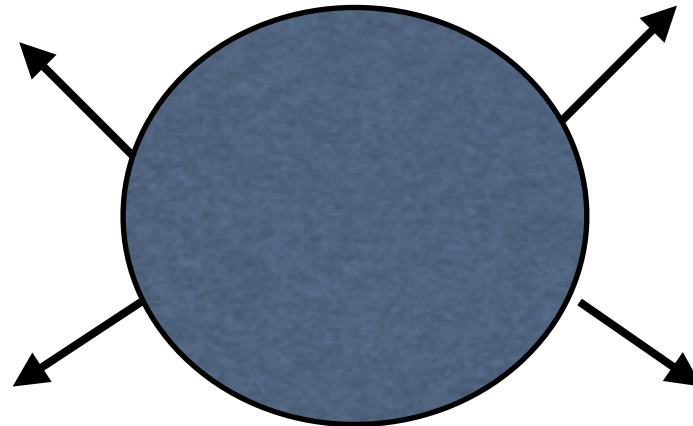
[Kawai, Lewellen, Tye;
Lerche, D.L. Schellekens, D.L.
Antoniadis, Bachas, Kounnas (1986)]

Flux vacua, KKLT: 10^{500}

[Bousso, Polchinski (2000);
Douglas (2003)
Kachru, Kallosh, Linde, Trivedi (2003)
Denef, Douglas (2004);

F - theory: 10^{272000}

[Taylor, Wang (2015)]



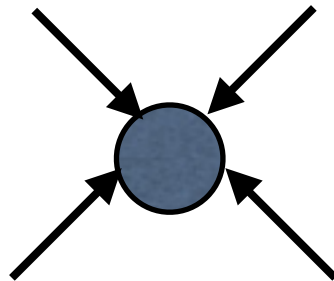
(Almost) anything goes ! - Multiverse & Anthropic principle

[Weinberg, Susskind, Schellekens, Linde,]

History of the landscape/swampland:

Now: Swampland constraints

The landscape is apparently shrinking again



(Almost) nothing goes !

Outline:

II) Some swampland conjectures

III) AdS distance conjecture

IV) Gravitino mass conjecture

V) Phenomenological consequences

II) Global symmetries, weak gravity & distance conjectures

No global symmetry conjecture:

[T. Banks, L. Dixon (1988); T. Banks, N. Seiberg (2011)]

A theory with a finite number of states, coupled to gravity, cannot have exact global symmetries.

E.g. global baryon number cannot be exactly preserved in quantum gravity !!

Now let us gauge the global symmetry, introducing an Abelian gauge coupling constant $g_{U(1)}$

Global limit $g_{U(1)} \rightarrow 0$ is apparently obstructed.

Weak gravity conjecture:

[N. Arkani-Hamed, L. Motl, A. Nicolis, C. Vafa (2007)]

$$S = \int d^4x \sqrt{-g} \left(\frac{M_p}{2} R - \frac{1}{4g_{U(1)}^2} F^2 \right)$$

Electric version:

There always exists a particle in the theory with mass m and charge q , satisfying

$$m_q \leq g_{U(1)} |q| M_p$$

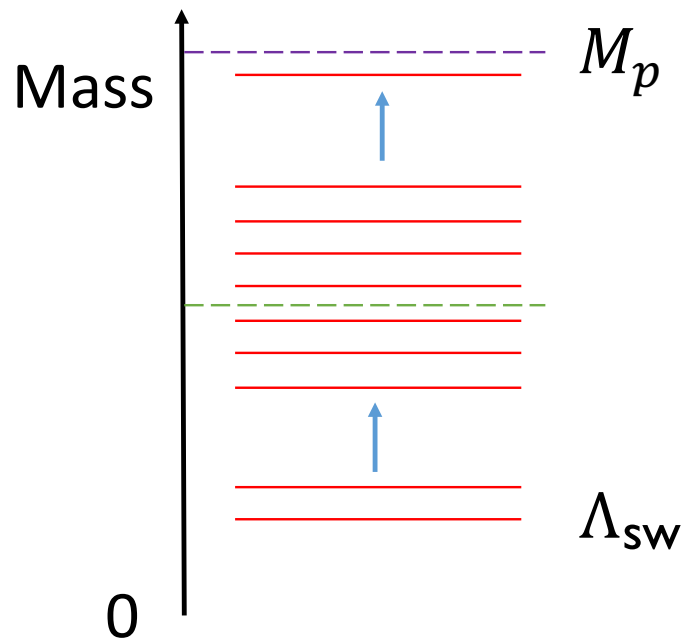
Magnetic version:

Cut-off of the effective theory is bounded from above as $\Lambda \leq g_{U(1)} M_P$

EFT typically breaks down above a swampland scale Λ_{sw} .

If swampland scale Λ_{sw} is lower than any characteristic energy scale of the EFT then the entire EFT belongs to the swampland.

Often there is an (infinite) tower of states above $E \geq \Lambda_{sw}$



Swampland distance conjecture:

At large distance Δ directions in the parameter space of string vacua there must be an infinite tower of states with mass scale m .

SDC:

$$m = M_P e^{-\Delta}$$

[H. Ooguri, C. Vafa (2006)]

EFT breaks down at $\Lambda_{sw} \equiv m$.

$$\Lambda_{sw} \ll M_P \text{ when } \Delta \rightarrow \infty$$

In general Δ determines the geodesic distance in the ϕ - parameter space of backgrounds in gravity: $\Delta = \Delta(\phi)$

$$\mathcal{L}_{eff} \simeq \frac{1}{2} (\partial\Phi)^2 + (V(\Phi)) \text{ with } \Phi = \Phi(\phi)$$

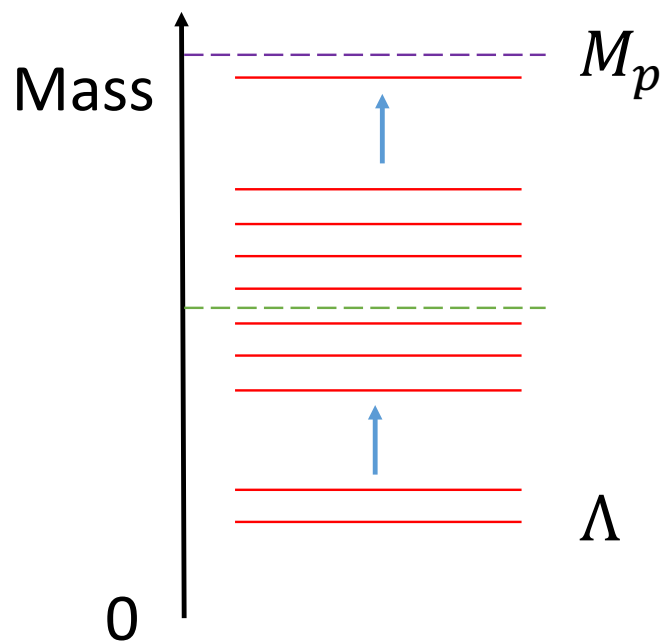
$$\implies \Delta = \lambda \Phi$$

For (string) compactifications the SDC is often due to the higher dimensional nature of theory:

At the KK mass scale a new dimension is opening up.

For a compact circle of radius R , the relevant mass scale is

$$m = m_{KK} = 1/R, \quad \Delta_{KK}(R) = \log R$$



The relevant tower are the **KK particles** with masses

$$m_n = \frac{n}{R}$$

and also with U(1) gauge couplings

$$g_{U(1)} = \frac{1}{R}$$

Quantum gravity/string vacua are normally characterised by several parameters, like masses or other couplings,

$$g = g(\phi), \quad m = m(\phi)$$

and we like to know, what is happening in certain (infinite distance) limits, e.g.

$$g \rightarrow 0 \quad \text{or} \quad m \rightarrow 0$$

and in particular, if these limits are obstructed in quantum gravity in the sense that they related to lowering the cut-off of the theory and are accompanied by a tower of light states.

III) AdS distance conjecture:

Consider AdS_d vacua in quantum gravity with varying negative cosmological constant Λ_{cc} .

AdS Distance conjecture (ADC):

[D.L., E. Palti, C.Vafa (2019)]

There exist an infinite tower of states with mass scale m , which behaves as

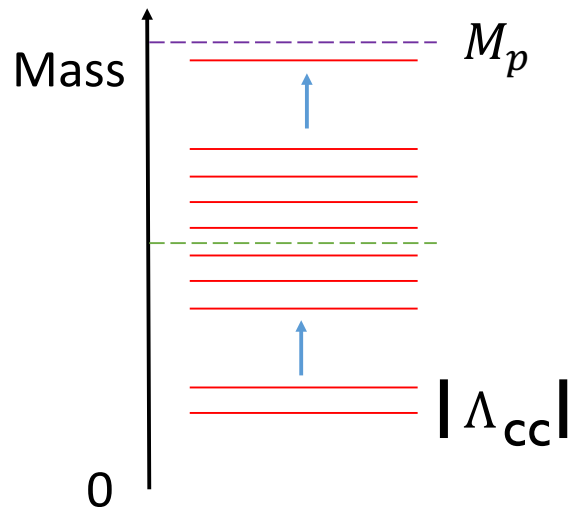
$$m \sim |\Lambda_{cc}|^\alpha \quad \text{with} \quad \alpha \geq \frac{1}{2}$$

AdS_d alone cannot exist as consistent background.
(Interesting implications for dual CFT description!)

[L.Alday, E- Perlmutter (2019), E. Perlmutter, L. Rastelli, C.Vafa, I.Valenzuela (2020)]

Strong AdS distance conjecture (SADC):

The bound $\alpha = 1/2$ is saturated for supersymmetric AdS vacua.



Infinite tower of states above Λ_{cc}

The conjecture is satisfied for many known backgrounds of string and M - theory like $AdS_5 \times S^5$ via the tower of KK modes.

Consider (meta-stable) vacua with positive cosmological constant and assume that the ADC is still valid :

Then, in the standard cosmological scenario, the ADC leads to a very strong prediction, namely to a very light tower of states:

$$m \sim 10^{-120\alpha} \quad (\text{in Planck units})$$

What could be this tower of states, and if it exists, can it escape observations?

Perhaps we need to refine the ADC for broken supersymmetry and also for vacua with $\Lambda_{cc} \geq 0$.

Gravitino mass conjecture (GMC):

[N. Cribiori, M. Scalisi, D.L. ; A. Castellano, A. Font, A. Harraez, L. Ibanez (2021)]

In the limit of small gravitino mass there exist an infinite tower of states with mass scale m , which behaves as:

$$m \sim (m_{3/2})^n \quad \text{with} \quad n > 0$$

For supersymmetric AdS spaces one has that

$$(m_{3/2})^2 = -\frac{\Lambda_{cc}}{3}$$

and the ADC and the GMC are equivalent to each other.

(Note that the case $m_{3/2} = 0$ is special and not continuously related to finite $m_{3/2}$.)

But in case of **broken supersymmetry** one has that

$$(m_{3/2})^2 > -\frac{\Lambda_{cc}}{3}$$

and the ADC and the GMC lead to different conclusions.

In particular the GMC allows for

$$|\Lambda_{cc}| \rightarrow 0 \quad \text{and} \quad m_{3/2} \text{ finite}$$

and without a tower of light states.

Why the GMC can be true:

(i) The gravitino mass is related to extra dimensions

The GMC follows from the distance conjecture.

(ii) The gravitino mass is related to a $U(1)$ gauge coupling

The GMC follows from the (magnetic) weak gravity conjecture.

(i) Extra dimensions

[See also I. Antoniadis, C. Bachas, D. Lewellen, T. Tomaras (1988)]

The $\mathcal{N} = 1$ effective action contains besides the graviton and the gravitino also a certain number of scalars ϕ (as well as their fermionic superpartners).

ϕ : Moduli parameters of the compactification

Their couplings in the effective action are determined by

Kähler potential: $K(\phi, \bar{\phi})$

Superpotential: $W(\phi)$

Kinetic terms of scalars:

$$\mathcal{L}_{eff} \simeq \frac{1}{2} K_{i\bar{j}} \partial\phi_i \partial\bar{\phi}_j + c.c$$

Supersymmetry breaking:

F-terms: $F_i \equiv e^{G/2} G_i = e^{K/2} |W| \left(K_i + \frac{W_i}{W} \right) \neq 0$

$$G(\phi, \bar{\phi}) = K(\phi, \bar{\phi}) + \log |W(\phi)|^2$$

Gravitino mass

$$(m_{3/2})^2 = e^{K(\phi, \bar{\phi})} |W(\phi)|^2 \equiv e^G$$

Scalar potential (cosmological constant):

$$V \equiv \Lambda_{cc} = V_G + V_F$$

$$V_G = -3e^G = -3e^K |W|^2 = -3(m_{3/2})^2$$

$$V_F = e^G G^{i\bar{j}} G_i G_{\bar{j}} \geq 0, \quad \implies \quad (m_{3/2})^2 \geq -\frac{\Lambda_{cc}}{3}$$

Consider a (string) compactification from 10 to 4 space-time dimensions on a compact (Calabi-Yau) space with volume \mathcal{V} .

KK mass scale:

$$m_{KK} = \left(\frac{1}{\mathcal{V}} \right)^{2/3}$$

$$K(\phi, \bar{\phi}) = -\alpha \log \mathcal{V}(\phi, \bar{\phi}) + K'$$

$$\langle W \rangle \sim \mathcal{V}^{\beta/2}$$

$$\implies m_{3/2} \sim \left(\frac{1}{\mathcal{V}} \right)^{\frac{\alpha-\beta}{2}} \quad \text{Hence} \quad n = \frac{4}{3(\alpha-\beta)}$$

Supersymmetric (KKLT) AdS vacua: [S. Kachru, R. Kallosh, A. Linde, S. Trivedi (2003)]

$$K = -3 \log(T + \bar{T}) + \dots = -2 \log \mathcal{V} + \dots$$

$$\langle W \rangle \sim T e^{-cT}$$

R. Blumenhagen, M. Brinkmann, A. Makridou (2019)

$$n = 1/3 \quad + \text{log corrections}$$

Non-supersymmetric Minkowski vacua (Scherk-Schwarz):

[J. Scherk, J. Schwarz (1979); E. Cremmer, S. Ferrara, C. Kounnas, D. Nanopoulos (1983), R. Rohm (1984)]

$$K = -\log[(S + \bar{S})(T + \bar{T})(U + \bar{U})] + K'(\phi, \bar{\phi})$$

$$W = \text{const} \quad n = 4/3$$

Non-supersymmetric dS: anti-brane uplift

[G. Dvali, H. Tye (1999); S. Kachru, R. Kallosh, A. Linde, S. Trivedi (2003)]

$$V_{dS} = V_{AdS} + V_{up}, \quad V_{up} = \frac{c}{\mathcal{V}^p} \quad n = 1/3$$

(ii) U(1) gauge coupling

In case there is an underlying extended space-time supersymmetric, the gravitino is charged under an U(1) gauge symmetry.

E.g. $\mathcal{N} = 2$ supersymmetry:

Extended supergravity supermultiplet:

(Spin-2, spin-3/2, spin-1)

Graviphoton U(1) gauge boson

Prepotential:

$$m_{3/2} \simeq g_{3/2}$$

$$g_{3/2} \rightarrow 0 \implies m_{3/2} \rightarrow 0 \quad \text{Global symmetry !}$$

V) Applications:

(i) Quantum gravity cutoff in an EFT with susy breaking.

N: number of light species in an EFT.

Gravity becomes strongly coupled at the species scale.

[G. Dvali (2007)]

$$\Lambda_{QG} = \frac{M_P}{\sqrt{N}}$$

If species are built by the tower of states we get $N = \frac{\Lambda_{QG}}{m}$

For the gravitino mass conjecture we then get

$$\Lambda_{QG} \simeq M_P \left(\frac{m_{3/2}}{M_P} \right)^{\frac{n}{3}}$$

So $m_{3/2} < \Lambda_{QG}$ if $n < 3$

$$n \geq 3 \implies$$

No effective field theory of supersymmetry breaking.

For a charged gravitino we have the bound

$$\Lambda_{QG} < g_{3/2} M_P$$

Then we obtain the following relation

$$m_{3/2} < (g_{3/2})^{3/n} M_P < g_{3/2} M_P$$

This can be true for $n < 3$

(ii) Inflation and supersymmetry

The mass scale of inflation in the EFT is determined by the Hubble parameter H .

For consistency one needs $H < \Lambda_{QG}$

This translate into the following lower bound on the gravitino mass

$$m_{3/2} > M_P^{\frac{n-3}{n}} H^{\frac{3}{n}}$$

For $n = 3$ $m_{3/2} > H$

[see also R. Kallosh, A. Linde (2004)]

Susy breaking scale must be higher than the scale of inflation!

CMB and the scalar-to-tensor ratio r :

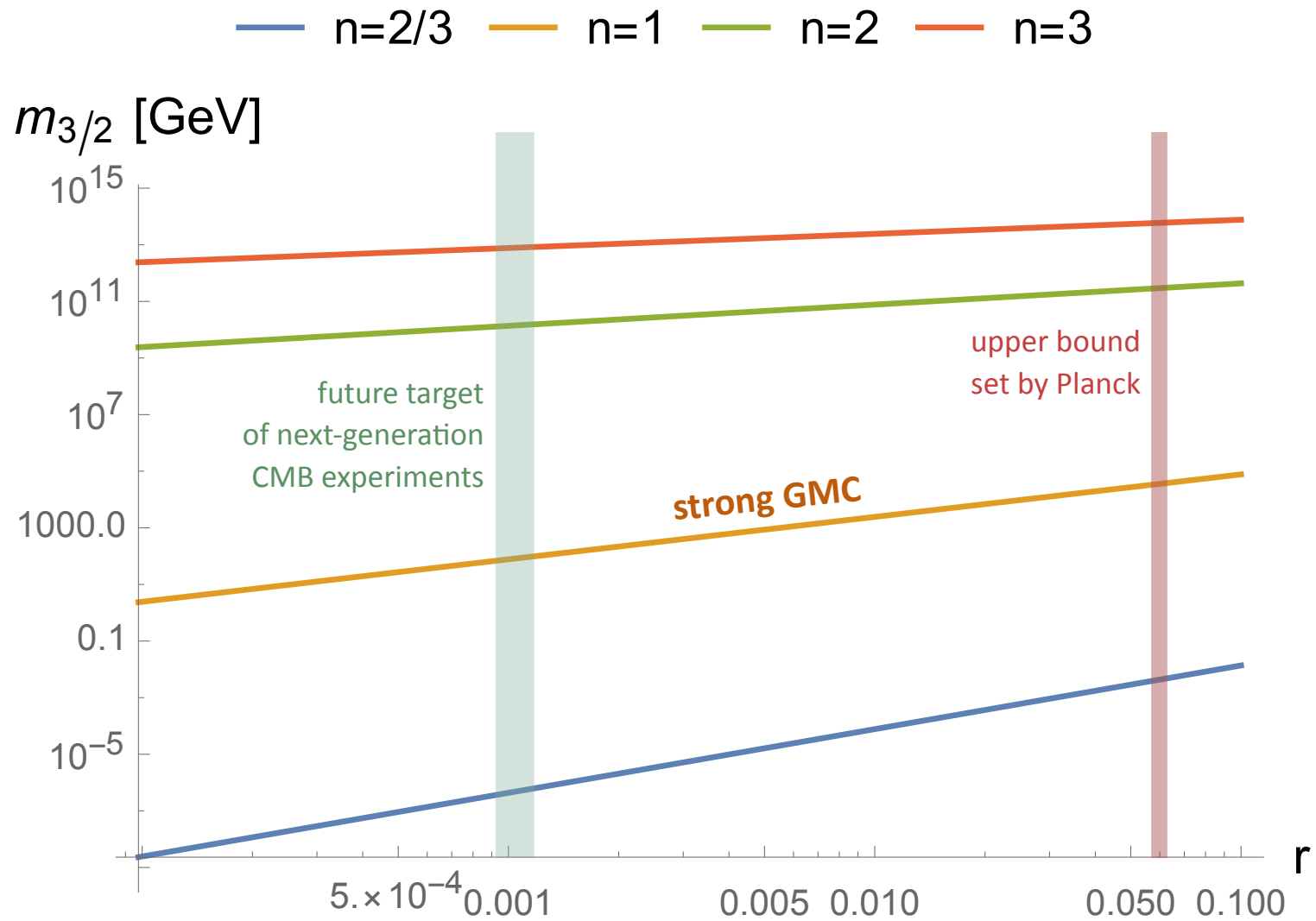
$$H = \sqrt{\frac{\pi^2 A_s r}{2}} M_P \simeq 10^{-4} \sqrt{r} M_P$$

So we get $m_{3/2} > \left(10^{-12} r^{\frac{3}{2}}\right)^{\frac{1}{n}} M_P$

Currently $r_{exp} \lesssim 0.06$

Next CMB experiments try to reach $r = \mathcal{O}(10^{-3})$

So one can reach $m_{3/2} \geq 10^2 \text{ GeV} \quad (n = 1)$



V) Outlook:

- There are various swampland conjectures, motivated from strings and black holes.

Many of them are related and hinting at a deeper common origin.

- Two specific swampland conjectures:

ADC: Λ_{AdS} is setting the cut-off of the theory.

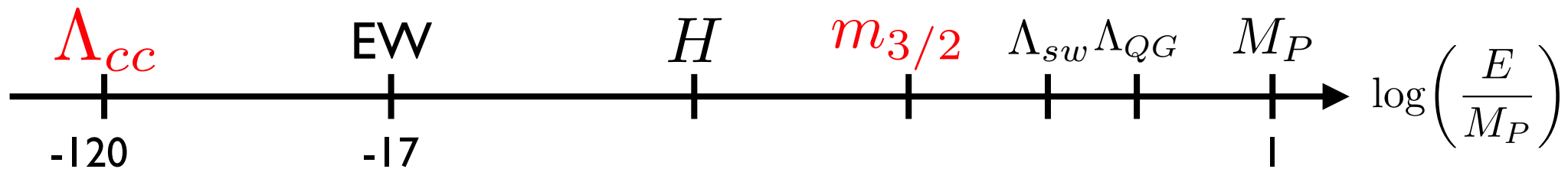
GMC: $m_{3/2}$ is setting the cut-off of the theory.

Perhaps there is parametric link of the form

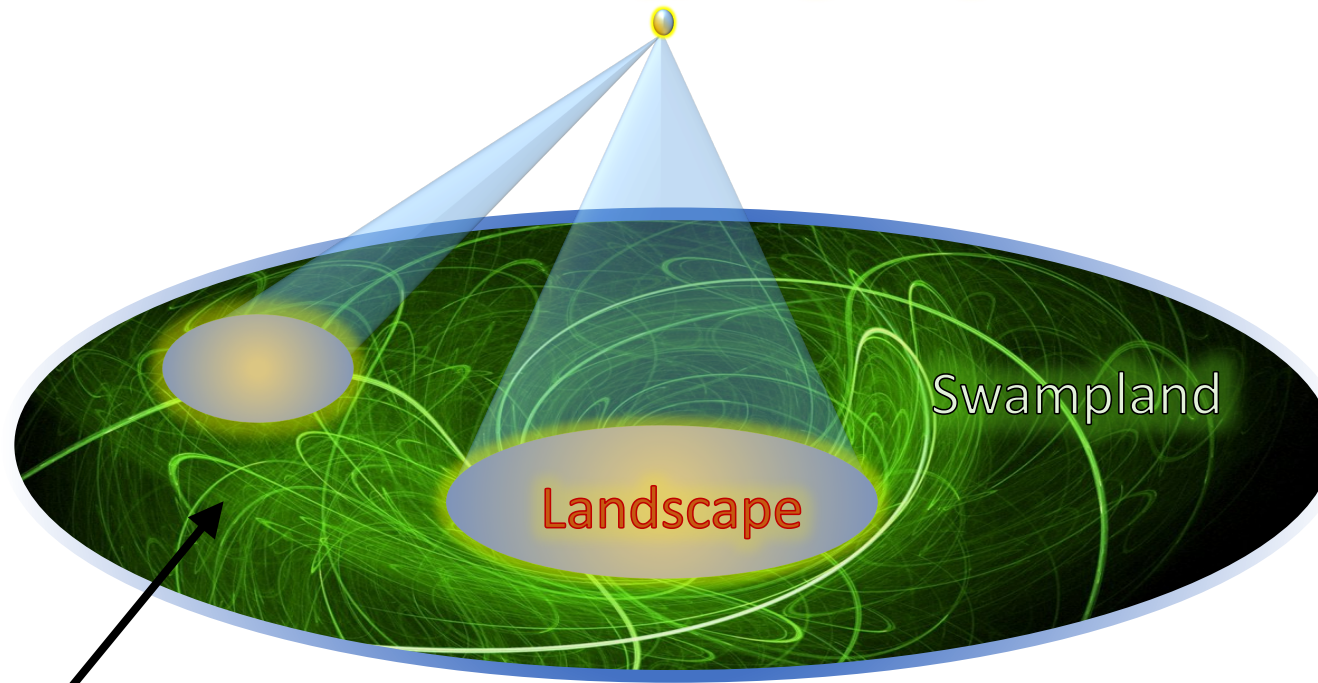
$$m_{3/2}^2 \sim |\Lambda|^p$$

Strong constraints from inflation on $m_{3/2}$

Susy breaking scale is of order or higher than the scale of inflation!



Quantum Gravity / String Theory



Low energy supersymmetry apparently belongs to the swampland !

Thank you !